TREATED WASTEWATER IRRIGATION: HOW TO MANAGE WATER SALINITY WITHOUT REDUCING ITS NUTRIENTS CONTENT?

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Abstract:
Context and purpose of the study - Nutrients in municipal treated wastewater (N, P, K, mainly) are a particular advantage in this source over conventional irrigation water sources, so supplemental fertilizers would sometimes not be necessary. However, additional environmental and health requirements are taken into account for this source of irrigation water. Most treated wastewaters are not very saline. Salinity levels usually ranging between 500 and 2000 mg/L (ECw = 0.7 to 3.0 dS/m). However, there may be instances where the salinity concentration exceeds the 2000 mg/L. Anyway, appropriate water management practices should be followed to prevent soil salinization, regardless of the salt content of the treated wastewater and plant sensibility. The ability of soil to self–cleanse in each rain event decreases the salinity supplied with treated wastewater, but this will depend on the balance between supply-water and rain-water. The aims of this study were to assess the effect of fertigation with municipal treated wastewater, on the soil-plant-fruit-wine system and the need, in some cases, to control salinity thresholds (Na^+ and Cl^- ions) of irrigation water by membrane technology.
Material and methods - Two experimental vineyards of Viognier B and Carignan N. were monitored for growing seasons 2017 and 2018. Two different water sources were compared: drinking water (DW) and municipal treated wastewater (TWW) at two irrigation levels by drip irrigation system. Vegetative growth was monitored once a week. Berry fresh weight and juice composition (primary metabolites) were determined at harvest. Soil sampling was carried out at postharvest for analytical determinations. Given that, in the event of low rainfall, excess sodium and chloride resulting from irrigation with TWW are not leached from the soil. This paper looks at the process membrane technology, most adapted by which salt levels in irrigation water can be reduced.
Results - TWW played a substantial role in the shoot growth and the variation of irrigation level caused significant difference compared to the irrigation with DW. Moreover, yeast assimilable nitrogen was higher in grapes from vines irrigated with TWW. Wine sensorial quality was mainly influenced by irrigation levels. Results showed a higher Na_2O content in soils that have received TWW. Success in using TWW for crop production will largely depend on adopting appropriate strategies aimed at optimizing crop yields and quality, maintaining soil productivity and safeguarding the environment. Electrodialysis, from homogeneous membranes technologies does not filter the water, but extracts a quantity controllable in line of dissolved salts (Na^+ and Cl^- in particular selectable) under the effect of an electric field, in order to adapt to the soil or crop concerned. In the context of vineyard sustainability and an eco-responsible approach, electrodialysis can be seen as an agricultural water treatment technology reliable and fit for purpose.

Keywords: Grapevine, irrigation, treated wastewater, fertigation, control water salinity, electrodialysis.

1. Introduction

Water quality is the most important issue in treated wastewater (TWW) management for Irrigation. As well as, it is essential in arid and semi-arid zones where extremes of temperature and low relative humidity result in high rates of evaporation with consequent deposition of salt, which tends to accumulate in the soil profile. As a rule, water quality recommendations are set by international guidelines (Ayers and Westcot, 1985) and regulations (according to country legislation), depending on the type of reuse or crop specificities.

However, additional environmental and health requirements are taken into account for use this source of irrigation water. Nutrients in municipal TWW –nitrogen, phosphorus, potassium, zinc, boron and sulfur, mainly– have a particular advantage of this source over conventional irrigation water sources (Metcalf & Eddy Inc., 2007), so supplemental fertilizers would sometimes not be necessary (Jiménez-Cisneros, 1996; Zavadil, 2009; Etchebarne *et al.*, 2019). The physical and mechanical properties of the soil, such as soil structure (stability of aggregates) and permeability, are very sensitive to the type of exchangeable ions present in irrigation water. Thus, when TWW reuse is being planned, several factors related to soil properties must be taken into consideration, because soil salinity is related to, and often determined by, the salinity of irrigation water. Most municipal TWW are not very saline, though to increase salinity could be due to: salts added by urban water use and infiltration of saline water into sewers –in coastal area. Salinity levels usually ranging between 500 and 2 000 mg/L (EC_w = 0.7 to 3.0 dS/m). However, there may be instances where the salinity concentration exceeds the 2 000 mg/L. Some dissolved mineral salts are identified as nutrients and are beneficial for plant growth, while others may be phytotoxic or may become so at high concentrations (e.g. B, Cl^- and Na^+). Each can cause damage individually or in combination (Fipps, 2003; Metcalf & Eddy Inc., 2007). Sodium is a unique cation because of its effect on soil. When present in the soil in exchangeable form, Na^+ causes adverse physical-chemical changes, particularly to soil structure (Fipps, 2003; Laurenson *et al*., 2012). As a rule, TWW reuse could be a source of excess Na^+ in the soil compared to other cations (Ca^{2+}, K^+, Mg^{2+}), and the resulting high sodium adsorption ratio (SAR) is a major concern in planning water reuse projects. For this reason, the soil Na^+ accumulation should be monitored. By knowing both the EC_w and SAR, the likelihood of having a water infiltration problem can be predicted (Ayers and Westcot, 1985, Metcalf & Eddy Inc., 2007). The ability of soil to self–cleanse in each rain event decreases the salinity supplied with treated wastewater, but this will depend on the balance between supply-water and rain-water (Etchebarne *et al*., 2019; Escudier *et al*., 2019). In need, to managing irrigation water salinity each specific case must be studied carefully in order to selecting the right desolation technology and water treatment (Martínez Beltrán and Koo-Oshima, 2006; Escudier *et al.*, 2019). The aims of this study were to assess the effect of irrigation with municipal TWW on the soil-plant-fruit-wine system and the need, in some cases, to control salinity thresholds (Na^+ and Cl^- ions) of irrigation water by membrane technology.

2. Material and methods

Experimental site and irrigation treatments –A two-year study (2017-2018) was conducted in two vineyards V. Vinifera cv. Viognier B. grafted onto SO4 rootstock (sandy loam soil) and Carignan N. grafted on R110 rootstock (limestone soil), under Mediterranean climate at INRA UE Pech Rouge, southern France (latitude 43°08'35''N; longitude 3°7'59''). The vines were planted in 1996 and 1983, respectively, and spaced to 1 m x 2.5 m with a northwest-southeast orientation. Viognier B vineyard is cultivated on cane-trained system (single Guyot prunning) with a three-wire VSP trellis system and Carignan N on spur-trained system with a canopy free trellis goblet system. The experimental plots were drip irrigated and two factors were examined: irrigation water type and amount. Two water qualities were used: drinking water (DW= control) and municipal treated wastewater (TWW = tertiary treatment with filtration, disinfection UV and chlorination). Each water type was supplied at two irrigation levels: 1 (based on measures of vine water status, Ψ_{pd}, from berries pea-size) and 2 (starting after budburst, at flowering, then based on measures of vine water status with reinforced at veraison and postharvest irrigation). In all, four treatments per experimental plot and three replicates for each treatment.

Vegetative growth measurements – Budburst, flowering and veraison stages, as defined by Coombe (1995), were recorded in each experimental vineyard. Relative shoot elongation was determined by measuring shoot length once a week from inflorescence well developed stage (E-L stage 17, Coombe, 1995) until the point where vegetative growth stopped. On post-harvest, the lateral shoots in each of the main shoots were counted and measured. Vine leaf area was assessed by shoots leaf area (main and laterals) and shoots length (Etchebarne *et al.,* 2019).

Harvest, winemaking and assessment–Cluster number per plant were determined at harvest, together with cluster and berry fresh weight. Berry juice total soluble solids concentration (TSS, °Brix), pH, titratable acidity (TA), malic (M) and tartaric (T) acids and yeast assimilable nitrogen (YAN) content were measured.The harvest 2017 was vinified (four treatment irrigated and one without irrigation, per two grapevine cultivars) and wines have been subject to a sensory evaluation conducted from expert jury.

Soil measurements – Soils were sampled in 2013, before the beginning of experiments with treated wastewater and then, at the end of each season (out at postharvest), for chemical and physical analysis. No significant difference was observed between different treatments (data not shown). Monitoring sodium accumulation in soil was carried at the end of each irrigation season (2017-2018). Fifteen samples were collected in each experimental vineyard (four treatments irrigated compared to one without irrigation), so three replicates by treatment (at 0–20 cm depth in Viognier B and 0–10 cm in Carignan N). Composite samples were prepared by mixing the three replicates of each and sent to a commercial laboratory.

Statistical analysis **-**Statistical analysis was carried out with InfoStat software, student version 2016 (National University of Córdoba, Argentine) for Windows. The possible significant differences among samples according to the different factors considered in this study were established by analysis of variance (ANOVA) and means were separated by Fisher's least significant difference (LSD) test ($p > 0.05$).

3. Results and discussion

3.1. Precipitation and irrigation water

The amount of annual and growing season rainfall fluctuated significantly among the two experimental years. In 2018, it exceeded by 152% (annual rainfall) and 310% (growing season rainfall), compared to precipitations 2017 (Table 1). The average seasonal irrigation amounts varied in order to seasonal precipitation and vine water needs (Table 1). TWW quality complied with French legislation (NOR: AFSP1410752A). Results showed that in addition to the water profit as part of a circular economy, the fertilizer contribution of the TWW would be important, according to the plant's nutrient needs, as demonstrated above (Etchebarne et al., 2019). In 2017 and 2018, TWW contained: 42–45 mg/L of total nitrogen (N), 1.2–2.1 mg/L of phosphorus (P) and 29 mg/L of potassium (K). Thus, the water volume supplied with TWW-irrigated treatments (Table 1) would have contributed with 48–98% N, 5–11% P and 23–47% K in 2017, and 23–85% N, 4–16% P and 10–37% K in 2018, according to fertigation advice for wine grape (expected yield from 40 to 60 hL/ha). The pH and electrical conductivity (EC_w) of irrigation water applied remained relatively stable (pH 8 and EC_w 1.6 dS/m). However Na^+ and Cl^- content, and water SAR increased between 2017 to 2018 (Na^+ 106 to 190 mg/L, Cl^- 230 to 284 mg/L, SAR 3 to 4). In current climate change situation (increase/decrease annual and seasonal rainfall, temperature and crop potential evapotranspiration), controlling/refining TWW salinity level is necessary but without reducing of its nutrients (mainly N, P and K). This is possible by only electrodialysis –perm-selective membranes technology (Berk, 2013), and may add to prevent soil degradation by salinization because the primary man-made cause of salinization is irrigation (Bless *et al*., 2018; Escudier *et al*., 2019). Reverse osmosis and also nanofiltration technology remove correctly the salts but also nutrients as nitrogen, phosphorus, potassium.

3.2. Soil and Na^+ concentration

Soil Na concentrations –at the end of the irrigation season, for the irrigation treatments with TWW were higher than that in irrigation treatments with DW and without irrigation (NI) (Table 2). Soils with high Na concentration may result in preferential uptake of Na at the expense of Ca and Mg that can lead to nutrient deficiencies in the vine (McCarthy, 1981; Grattan and Grieve, 1998). Thereby, it will be necessary monitoring these parameters and possible grapevine deficiencies over the growing season. It should be noted that between the last irrigation and soil sampling, no rain was recorded for 'Viognier B' plot; but low rainfall (5.5 mm) in 2017 and high rainfall (207 mm) in 2018 were recorded during this time interval for 'Carignan N' plot. Results highlight the soil's ability to self–cleanse at each rain event would decreases the salinity supplied with treated wastewater, but it will depend on ratio supply-water/rain-water (Table 1).

3.2. Vegetative growth, yield, yeast assimilable nitrogen concentration, and wine quality

The final effect of irrigation on shoots length, leaf area (total LA/vine) and yield (Table 3) varied from an experimental vineyard to another, probably due to differences in the vine vigour and soil nutrients and water availability. It should be noted that Carignan' shoots were trimmed at bunch closure stage (E-L stage

33, Coombe, 1995). Water quality interacted with irrigation level such that the response of vegetative growth to irrigation was more when TWW was used, and exerted a significant impact on leaf area and yield (Table 3). The evident yield differences recorded between seasons were due to the soil water available –from rainfall mainly– and the water quality treatments (Table 3). Berry juice YAN (yeast assimilable nitrogen) was significantly higher in vines irrigated with TWW-2 (reinforced irrigation) for both Viognier B and Carignan N. However, the YAN concentration level in berry juice of non-irrigated vines from Carignan N plot would be showing the nitrogen availability in the soil, as indicated in preliminary results (Etchebarne *et al*., 2019). Results wine chemical analysis does not allow any conclusions to be drawn (data not shown). However, sensory analysis showed that the irrigation strategy is greatest impact factor on the organoleptic differentiation of wines. The effects of water amount supplied can be accentuated by water quality or the availability of water in the soil. In any case, microvinifications repetitions are absolutely necessary to be able to properly evaluate the various factors studied. Similarly, rigorous monitoring in the medium to long term would make it possible to properly integrate the variability linked to the vintage effect.

3.3. Brackish water desalination by EDR

Electrodialysis reversal (EDR) technology is based on the principle of electrolysis, combined with anion and cation membranes that operate in a similar way to ion exchange. Therefore, the energy supplied for the process takes the form of an electric potential difference (direct current) where dissolved ions are attracted towards cathode and anode and transferred through the membranes. Thus, the feed flow becomes progressively less saline, and eventually becomes the product flow channel. The process is particularly suitable for brackish water with total dissolved solids (TDS) up to 10 g/L because the amount of energy required is directly proportional to the amount of salts to be removed (Table 4). In fact, with low-salinity waters, the process only requires a reasonable energy consumption (0.5–1.4 kWh/m^3), adjustment of the brine compartment with HCl, and cleaning in place procedure (with HCl / NaOH) can be considered on a regular basis of 1–2 per month (3 hours required) depending on water composition (Table 5). According to FAO expert group, membrane technologies are being most adaptable and considering EDR being promising for future applications (Martínez Beltrán and Koo-Oshima, 2006). The units can be designed in stages to reach low salinities, and require little pre-treatment, being suitable for waters such as TWW for agricultural irrigation. . As example, the figure 1 shows a perfect stability of desalination, electrodialysis removes only the excess of salts (constant reduction rate of conductivity) keeping the residual of nutrients in water. In the context of water quality management and a circular economy approach to resources motivated by both technical and economic considerations, electrodialysis can be considered with reasonable electricity consumption and operating cost. In this case it can therefore be seen as an agricultural water treatment technology that stands the test of sustainability and is reliable and fit for purpose (Escudier *et al*., 2019).
Over the years, a number of EDR plants have been installing in several locations on the world. About twelve tertiary treatment units (sand filtration, UV disinfection and/or chlorination) which includes desalination by EDR are now in operation in the Canary Islands, totaling some 19 350 m^3/d, and ranging in plant size from 200 to 6 000 m^3/d (FCCA, 2013).

4. Conclusions

The irrigation with TWW has a degree of similarity to fertigation, but nutrients concentrations and contents would be directly linked to wastewater origin (town-country), as well as to treatment techniques used by wastewater treatment plant. In this study, the vegetative growth and yield of Viognier B and Carignan N were significantly affected by the combined effect quality and quantity of irrigation water, in relation to variability seasonal and annual rainfall. Vines exposed to continuous TWW irrigation, show an interesting N accumulation in berry juice, whereas N levels in vines irrigated with DW and without irrigation (NI) were low and stable along the two studied years. Wine sensorial quality was mainly influenced by irrigation strategy. Nevertheless, the observed trends of Na^+ accumulation in the soil exposed to TWW may pose a potential risk at medium- long-term under conditions of low precipitations and high temperatures. To assess the suitability of brackish water for irrigation, a number of conditions must be taken into account, including: crop, climate, type soil, irrigation method, and management practices. Desalination of brackish TWW for agriculture is technically feasible and the most appropriate technology would be electrodialysis reversal

(EDR) in order to preserve a nutrient-rich water. EDR process allows controlling Na^+ and Cl^- removal and water quality by adjusting amount of electricity applied to membrane stack, and thus provides high water recovery. Therefore, only economic and strict environmental (in regard to brine discharge) considerations could limit its application.

5. Acknowledgments
This research was supported through a grant from the International Organisation of Vine and Wine (OIV), and executed under the Irri-Alt'Eau Observatory program with the French National Institute for Agricultural Research (UEPR and LBE). This program has benefited from public co-financing: ERDF Funds, Occitanie Region, Bpifrance, Corsica Rhone Mediterranean Water Agency and Grand Narbonne Agglomeration Community, and private: Veolia water, Aquadoc, Gruissan Wine Cellar Cooperative. The authors would like to thank P. Aveni, F. Prot, R. Saye and J.-J. Regadera for their assistance in field and/or laboratory work.

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Table 1: Seasonal growing conditions and amount of water applied in the two irrigation levels (1 and 2) during 2017 and 2018.

Season	Rainfall (mm)		ET† (mm)	Irrigation (mm)			
				Viognier B		Carignan N	
	AR	GSR†		1	2	1	2
2017	302	115	946	50	95	45	90
2018	760	471	958	20	67.5	30	75

AR, annual rainfall; GSR, growing season rainfall; ET, evapotranspiration (Penman method modified by Doorenbos & Pruitt, 1977); † from 1 April through 31 October. 1, standard irrigation; 2, reinforced irrigation.

Table 2: Na+ concentrations (g Na_2O/kg) of soil sample at 0–20 cm depth in Viognier B and 0–10 cm in Carignan N under two levels of irrigation and water quality treatments, compared to once non-irrigated.

Na^+ (g Na_2O/kg)	Viognier B 2017	Viognier B 2018	Carignan N 2017	Carignan N 2018
DW-1	0.06	0.10	0.03	nd
DW-2	0.04	0.03	0.05	nd
TWW-1	0.14	0.15	0.07	0.03*
TWW-2	0.21	0.18	0.16	0.08*
NI	0.10	0.05	0.02	0.02*

nd, not determined ; *concentration measured after 207 mm of rainfall

Table 3: Vegetative growth, yield and yeast assimilable nitrogen (YAN) concentrations in berry juice recorded on Viognier B and Carignan N grapevines for each irrigation level and water quality treatment, compared to once non-irrigated.

Year		Treatment	Shoot length primary (cm)	N° Shoot lateral	∑ Shoot length lateral (cm)	Total LA/ vine (cm^2)	Yield (T/ha)	YAN (mg/L)
2017	**Viognier B**							
		DW-1	72 a	7 a	34 a	7 036 a	5.28 b	71 ab
		DW-2	80 ab	7 a	28 a	7 696 ab	4.99 b	56 a
		TWW-1	88 ab	9 ab	46 ab	8 461 ab	5.54 b	109 bc
		TWW-2	92 b	11 b	70 b	8 911 b	6.05 b	115 c
		NI	nd	nd	nd	nd	4.00 a	40 a
	Carignan N							
		DW-1	144 a	5 a	55 ab	44 084 a	6.73 a	48 a
		DW-2	185 b	7 b	54 ab	54 342 ab	6.84 a	59 a
		TWW-1	139 a	5 a	30 a	42 621 a	8.82 a	52 a
		TWW-2	217 b	7 b	101 b	66 263 b	11.30 b	79 b
		NI	nd	nd	nd	nd	8.17 a	67 ab
2018	**Viognier B**							
		DW-1	96 a	9 ab	25 ab	12931 a	8.06 a	56 a
		DW-2	112 b	11 bc	58 bc	15177 b	9.41 ab	73 ab
		TWW-1	107 ab	10 abc	43 abc	14342 ab	10.08 ab	115 b
		TWW-2	118 b	12 c	73 c	15734 b	11.09 b	181 c
		NI	97 a	7 a	20 a	12946 a	7.97 a	68 ab
	Carignan N							
		DW-1	163 abc	5.67	26	65105 ab	14.34 a	87 a
		DW-2	170 bc	6.67	27	67360 b	15.51 a	119 b
		TWW-1	162 ab	5.44	24	64732 ab	15.47 a	108 ab
		TWW-2	175 c	4.78	18	69309 b	20.85 b	131 b
		NI	157 a	6.33	18	62210 a	13.17 a	111 ab

Data are means of each treatment. Each value represents n=12 for shoot length primary; n=6 for LA/vine; n=30 for yield; and n=3 for juice samples. Different letters within columns for each grapevine indicate a significant difference at $p < 0.05$ (LSD test). LA, leaf area; nd, not determined; DW, drinking water; TWW treated wastewater; NI, non-irrigated; 1, standard irrigation; 2, reinforced irrigation.

Table 4. Example of the salinity level treated wastewater and electrodialysis process performance.

Water quality adjusted by electrodialysis		
	Before treatment	**After treatment**
EC_w (dS/m)	5.59	1.0 – 1.3
TDS (g/L)	3.19	0.65 – 0.8
TH	41.7	7 - 10
Cations (mg/L)		
Sodium	980	120 - 220
Potassium	90	6 - 11
Magnésium	40	5 - 10
Calcium	100	15 - 20
Anions (mg/L)		
Sulfates	280	50 - 70
Chlorures	1700	360 - 460
Technology performance		
Recovery (%)	90	
TDS removal (%)	75 - 80	
Total energy (kWh/m^3)	0,9	

Table 5. Water desalination for agricultural applications by electrodialysis: Process performance.

Electrodialysis process performance				
Capacity (m^3/h)	50 - 150			
Recovery (%)	90.4	87	85.2	84.2
TDS Inlet (g/L)	**1**	**2**	**3**	**4**
EC_w (dS/m)	≈ 1.7	≈ 3.4	≈ 5	≈ 6
TDS removal (%)	70 - 80	70 - 80	70 - 80	70 - 80
Transfer energy (kWh/m^3)	0.25	0.53	0.83	1.10
Pumping energy (kWh/m^3)	0.25	0.26	0.27	0.27
Total energy (kWh/m^3)	**0.50**	**0.79**	**1.10**	**1.37**

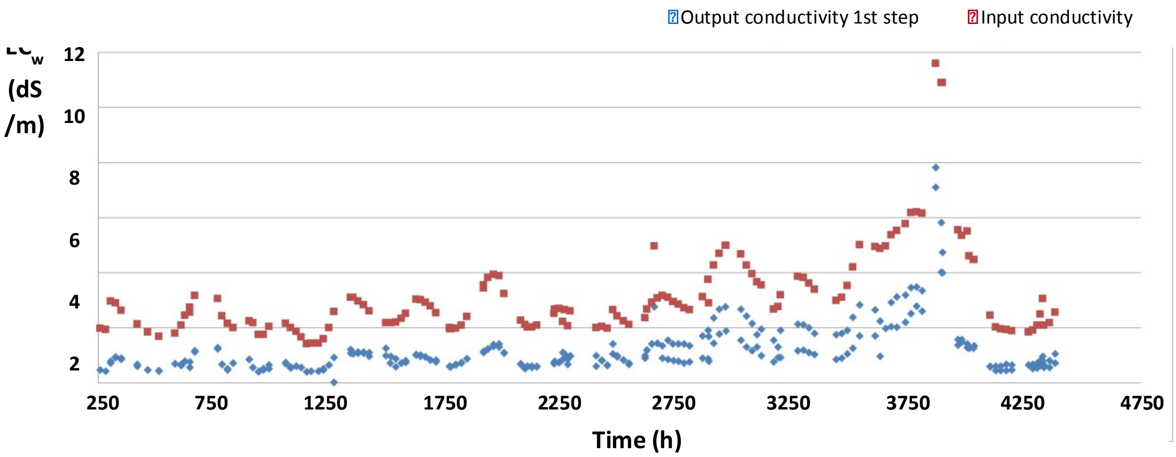

Figure 1. Water conductivity reduction by function of fluctuation of inlet salinity with electrodialysis reversal (EDR).